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The economics and greenhouse gas balance of land conversion to *Jatropha*: the case of Tanzania

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Abstract

Due to higher oil prices, abundance of labor and suitable land and its stable political climate, Tanzania attracted many investments in *Jatropha*. Although several studies on *Jatropha*'s economic potential are available, its true economics are still uncertain. This paper aims to add to the growing body of knowledge on the socio-economic performance of the *Jatropha* system by (i) studying the economic potential (net present value – NPV) of the current most prevailing *Jatropha* system for Tanzanian farmers and its regional differences, by (ii) making a greenhouse gas (GHG) balance and its economic value of the *Jatropha* activities on regional level, and by (iii) calculating break-even thresholds for yield and seed price. Therefore, regional yield modeling, regional life-cycle assessment, and NPV calculations based on Monte Carlo simulations, each with its set of assumptions, are combined. This study shows positive economic potential of *Jatropha* cultivation in most of the Tanzanian regions. However, the results also show that 13 of 20 Tanzanian regions will not attain a net positive GHG balance within 10 years. This indicates that the environmental impacts might be more restrictive for *Jatropha*'s sustainability potential in Tanzania than the socio-economic potential. These results are based on the combination of three models, which consists of strong interdisciplinary modeling work. However, this modeling also contains simplifications (e.g., no opportunity cost for 'marginal' land) and uncertainties (e.g., using globally modeled potential yield estimations), which have to be considered in the interpretation of the results.

Keywords: biodiesel, carbon debt, cost benefit, environmental impact, GHG balance, net present value

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Introduction

Biofuels have attracted more attention globally as substitutes for fossil fuel for transportation, heating, or electrification. Their potential benefits for reducing energy dependency on fossil resources, mitigating climate change, or enhancing economic development are nowadays increasingly questioned. The criticism on biofuels is based on the economic (e.g., indirect land use and food prices), social (e.g., food security), and environmental risks (e.g., loss of biodiversity and carbon stocks) related to their production (FAO, 2008; Fargione *et al.*, 2008; Mitchell, 2008; Searchinger *et al.*, 2008).

Jatropha curcas L. (further *Jatropha*) has taken a special place in this debate (Achten *et al.*, 2010). As a drought-resistant stem succulent tree (Maes *et al.*, 2009), *Jatropha* was claimed to be able to grow in dry and degraded areas unsuitable for food production not affecting food production directly nor indirectly. Similarly, converting these degraded areas to *Jatropha* plantations was assumed not to trigger significant losses of ecosystem carbon stock. Many countries, including India and China, consider *Jatropha* as potential contributor to attain renewable energy targets (Sang & Zhu, 2011; Das *et al.*, 2012). However, the claim that *Jatropha* can produce significant amounts of oil in such degraded areas has no solid scientific ground (Achten *et al.*, 2008; Das *et al.*, 2012). Therefore, massive expansion and investments hold socio-economic and environmental risks

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(Achten *et al.*, 2007, 2010). A good example of such investments, for a number of reasons described by Habib-Mintz (2010), is Tanzania (Hultman *et al.*, 2012). Strong *Jatropha* activity has been reported for Tanzania (GEXSI, 2008).

Information on the economic viability of the *Jatropha* system in general is limited and contradictory (Van Eijck & Romijn, 2008; Mulugetta, 2009; Wiskerke *et al.*, 2010; Mshandete, 2011). In his review Mshandete (2011), both cites studies that express concern about the low daily wages that can be achieved with Jatropha in Tanzania, but also cites Tanzanian research indicating that Jatropha hosts significant employment potential. Positive Jatropha stories often assume high yields (7000 kg ha^{-1}) and/or selling prices (US$ 0.18–0.40 per kg seeds) (Mulugetta, 2009), while negative stories are based on low-selling prices (US$ 0.05–0.06) (Van Eijck & Romijn, 2008; Wiskerke *et al.*, 2010). Using an economic land evaluation assessment Segerstedt & Bobert (2013) show for a specific Tanzanian large-scale Jatropha oil production case that high inputs (e.g., fertilizer and labor) and good soil are necessary to attain high yields (2000–5400 kg seed ha^{-1} yr^{-1}). However, these high inputs boost the production cost that is too high to render the activity profitable on the domestic or the international market. They further conclude that profitability will hinge on fossil and vegetable oil price increases (Segerstedt & Bobert, 2013).

A study on the role of Jatropha in different livelihood strategies of small-scale households in rural Tanzania shows that Jatropha is responsible for a significant share of the income (30%) of subsistence farm households that adopted Jatropha, whereas for households with cash crops and/or skilled off-farm employment, Jatropha contributes only 1–2% to the income (Faβe & Grote, 2013).

With this paper, we aim to add to the growing body of knowledge on the socio-economic sustainability of the *Jatropha* system by (i) studying the economic potential (net present value, NPV) of the current most prevailing *Jatropha* system for farmers (i.e., outgrower scheme), and for different selling options; (ii) identify the factors particularly important for value generation by; (iii) evaluating environmental risks and benefits for the Tanzanian society, by; (iv) calculating NPV break-even thresholds for yield and seed price and by; and (v) comparing small-scale systems with high-input systems as seen in commercial plantations.

In this paper, we estimate the NPV of *Jatropha* seed, oil, and soap production by private farmers in the marginal land types of 20 regions of the Tanzanian mainland. As the impact assessment takes place *ex ante,* uncertainty about the production and adoption variables is inevitable. The yield distribution used in our analysis is based on average climate conditions (Trabucco *et al.*, 2010), while farmers are confronted with unpredicted interannual variations of climate. Furthermore, accurate knowledge of agronomic practices, and its effect on Jatropha yields, is still largely unknown to scientist and farmers. Therefore, a model was run using Monte Carlo simulations. Following earlier papers from different fields, we rely on Monte Carlo simulations to account for this parameter uncertainty (e.g., Benke *et al.*, 2008; Demont *et al.*, 2008; Dillen *et al.*, 2010). As a result, we calculated the economic outcome of *Jatropha* production and its regional differences within Tanzania, performed scenario analyses on seed price and yield and identified threshold values for seed price and yield. This is very relevant information for a country in which the majority of initiatives is performed through outgrower schemes (Martin *et al.*, 2009). Furthermore, we evaluate potential risks or benefits for the Tanzanian society by evaluating the GHG emission reduction potential, using an adjusted generic life-cycle assessment model (Almeida *et al.*, 2011), carbon debt, and payback time (*sensu* Fargione *et al.*, 2008).

As such, this study shows mainly a modeling exercise. Three models, each with their assumptions, uncertainties, and limitations are combined. This interdisciplinary modeling effort is considered as a scientific contribution as well. The strengths and limitations of the modeling is therefore also discussed.

Materials and methods

Production system under research

As we aim to evaluate the economics of small-scale *Jatropha* activities for farming households on the one hand and examine the sustainability benefits of the production and use of *Jatropha* biodiesel for Tanzanian society on the other hand, both aspects of the *Jatropha* biodiesel production system are described.

Small-scale Jatropha farmers. For the definition of ‘small scale,’ a detailed assessment of the *Jatropha* value chain in Tanzania was made based on semistructured and in-depth interviews as well as workshops with the most important *Jatropha* stakeholders reported by Messemaker (2008). Based on this study, we describe the model *Jatropha* seed production system that is evaluated as follows:

It was observed that small-scale *Jatropha* farmers have plots ranging from 0.2 to 1.0 ha. The farmers acquire seedlings from nurseries. Nurseries are small-scale as well (not larger than 0.1 ha) and mainly managed by NGOs or private companies. After field preparation (clearing and making planting pits), the seedlings are planted in a 2.5 × 2.5 m plantation design (1600 plants ha^{-1}). Manure is applied in the planting pits. No further application of organic or inorganic fertilizer was observed after plantation establishment. The scarce weeding is carried out manually and, where possible, flood irrigation is used twice a year. No pesticides are used. Pruning is performed annually.

Harvesting of seeds is started 2 years after planting and is performed manually. A rotation period of 20 years was assumed.

For the initial investment of the farmer, we evaluated two scenarios. In the first scenario, the farmer opts to do a one-time investment, by planting all his available land at once with *Jatropha*. In the second scenario, the farmer chooses to invest continuously (e.g., with 1 ha available in a 20-year rotation, 80 individual plants are planted each year).

Seed processing. The seeds produced by small-scale farmers can be processed in different ways (Messemaker, 2008; Wiskerke *et al.*, 2010; Mshandete, 2011). In this research, we look into three alternative processing pathways (PWs). Two of them lead to biodiesel and one to soap.

In the first pathway (PW1), the farmer opts to sell seeds to a biodiesel production company. In that case, the farmer brings his seeds to the local collection point of that company. The company transports the seeds to a major city (we assume Dar es Salaam) where the oil is extracted with a mechanical screw press (1 kg oil from 3.64 kg seed (Achten *et al.*, 2008)) and converted to biodiesel (methyl esters through transesterification). The biodiesel is sold on the market in Dar es Salaam as transportation fuel. The seed cake is used as organic fertilizer and therefore has to be transported to the nearby fields where it is used.

In the second pathway (PW2), the farmer opts to extract the *Jatropha* oil himself using a manual ram press (Messemaker, 2008; Wiskerke *et al.*, 2010) (1 kg oil from 5 kg seed (Achten *et al.*, 2008)). The seed cake is used locally as organic fertilizer for other crops. The oil is sold to a biodiesel company that transports it to Dar es Salaam, converts it to biodiesel, and sells the biodiesel on the local market as transportation fuel.

In the third pathway (PW3), the farmer opts to extract the *Jatropha* oil himself and to process it into soap. The soap is produced by boiling oil, water, and caustic soda (Wiskerke *et al.*, 2010). The farmer therefore needs a tank, molds, fuelwood, and packaging material (Messemaker, 2008; Wiskerke *et al.*, 2010).

As there is a clear energy need in Tanzania and as there is an interest in biofuel, we assume that there will always be a biodiesel company prepared to buy the available *Jatropha* seeds or oil. For the third pathway, we assume that the soap market is not saturated and that the produced soap will be marketable.

Data sources

To calculate the NPV of *Jatropha* seed, oil, and soap produced by private farmers in the 20 regions of the mainland of Tanzania and the potential GHG reduction per region, we needed data on (i) *Jatropha* yields in these different regions; (ii) economic data on inputs and outputs (costs, prices, etc.); and (iii) the GHG emissions of *Jatropha* biodiesel production and use (following PW1 and PW2) compared with a reference system in which fossil diesel is used as transportation fuel. As we rely on Monte Carlo simulations to account for uncertainty, probability density functions (PDFs) were constructed for the important variables in the model instead of using fixed data points.

Yield data. For each Tanzanian region, yield data were extracted from a global *Jatropha* yield map (Trabucco *et al.*, 2010). These global yield estimates were generated by applying a two-step modeling approach. In a first step, *Jatropha*'s fitness to climate was predicted by relating natural occurrence distribution with bioclimatic geodatasets. In a second step, Jatropha fitness to climate was related to its reproductive potential, i.e., seed yield, by population biology principles supported by seed mass experiments. The yield map thus shows *Jatropha*'s suitability to climate factors from an ecological perspective. Therefore, they do not include impact of soil and the potential of agronomic practices to mitigate climatic stresses. Jatropha yield responses to climate are calibrated to naturally occurring individuals, equivalent to genotypes coevolved, and adapted to local climatic conditions. This yield map was validated by regression analysis between measured and estimated yields at specific locations ($R^2 = 0.674$, $P < 0.001$, $n = 15$). In a geographic information system (GIS), the *Jatropha* yield map of Tanzania (2 km resolution), containing inherent model uncertainty (see Trabucco *et al.*, 2010), was overlaid with a land cover map (300 m resolution) (ESA, 2009). The 22 classes of this land cover map were grouped into broader classes: mixed cropland, intensive cropland, forest, marginal, and other land use. To avoid competition with food production and with forest ecosystem services, we only selected the 'marginal' land-use types to be part of our analysis. This cluster contains: (i) mosaic grassland (50–70%)/forest or shrubland (20–50%); (ii) closed to open (>15%) shrubland (<5%); (iii) closed to open (>15%) herbaceous vegetation (grassland, savannas, or lichens/mosses); (iv) sparse (<15%) vegetation; and (v) bare areas.

Overlaying the spatial distribution of marginal lands on the *Jatropha* yield map identifies in tabular format the area distribution (km^2) for estimated Jatropha yield value associated with the marginal lands within each Tanzanian region. To construct a PDF of *Jatropha*'s yield potential and variability for each region, the area of marginal land within that region was proportionally divided over different yield classes [kg seed ha^{-1} yr^{-1}]. The resulting histogram (e.g. for Arusha in Fig. 1) with proportional bars for each yield class was then used to draw samples from in the Monte Carlo simulation model. The resulting average yield and standard deviation for each region are given in Table 1, together with a climate characterization of these regions following the Köppen classification scheme (Peel *et al.*, 2007).

The distribution of yields within a certain geographic region is a direct output of the yield model used. The modeled yield for a given grid cell is based on average climate conditions, while farmers have to confront unpredicted interannual variations of climate. Furthermore, accurate knowledge of agronomic practices, and its effect on Jatropha yields, remain unknown to scientist and farmers. Therefore, the variation within the region is assumed to be a proxy for the uncertainty faced by a farmer within the region.

Economic data. Most economic data on *Jatropha* were collected on-site by means of extensive field visits and interviews with the farmers, combined with on-site measurements. This also applies to the pricing data, which were collected from nurseries,

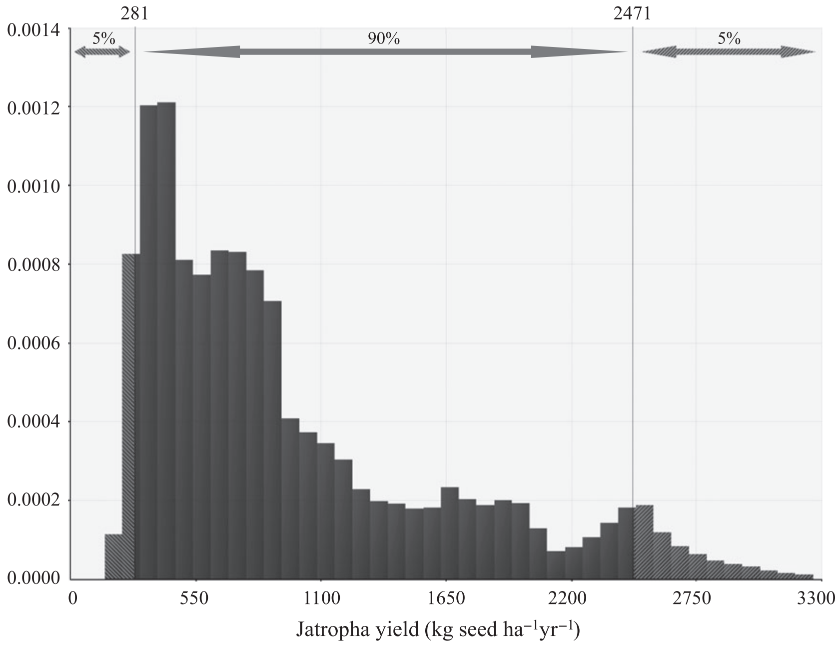

Fig. 1 Example of Jatropha yield distribution in the Arusha region.

farmers, collectors (resellers), and oil pressers themselves. Some prices were collected from larger firms as well. Background information related to policy was collected directly at the respective ministries (see Messemaker, 2008). As the results of the developed model prove very sensitive to the price of *Jatropha* seed, secondary sources were consulted to determine an appropriate range for the market price. The distributions we used are presented in Table 2.

Depending on the quality of the acquired price data and expert opinions, we constructed a triangular, a PERT (Program Evaluation and Review Technique) and a uniform PDF (Dillen *et al.*, 2009) as input of the Monte Carlo simulations. As data are limited, based on expert opinions, and scattered, a pragmatic approach was followed. As theoretical assumptions underlie the uncertainty around the market price and prices cannot be negative, the distributions used were selected for their transparency and fit to the data.

The probability functions defined as an input for the Monte Carlo have been constructed on the basis of the available data.

The available literature presents a wide range of possible prices for the seedlings. Therefore, a triangular distribution using the minimum, maximum, and most likely of the observations was taken to construct a triangular PDF. The advantage of the triangular distribution is its transparency for the reader as it has an easy shape and equation.

Less information is available on the price of oil. However, as the price is not fixed, we introduced some variation by assuming a minimum and maximum. In this case, the PERT distribution, a special case of the Beta distribution, was chosen, as it is less sensitive to the value of the extremes. The standard deviation is always smaller than for the triangular based on the same assumptions.

Finally, a uniform distribution is used to present the price range for soap. The uniform was chosen because of its transparency and the fact that no further information most likely values of averages was available.

The cost of inputs, such as pruning, irrigation, and harvesting, are assumed to be proportional to the growth stage of *Jatropha*, specifically following published trends of seed yield over time, and modeled using a Chapman–Richards growth model (Chapman, 1961) simulating sigmoidal growth with an asymptotic peak in growth after a certain age:

$$Y = a \times \left(1 - e^{-b \times X}\right)^{c} \tag{1}$$

where Y is the organism growth quantity to evaluate (in our case, seed yield and input costs), X is age, a is the asymptote or maximum achievable growth (seed yield at maturity), b is the growth rate, and c is the shape of the curve near the origin, respectively. Based on the two measured chronosequences in Allahabad (own observations) and Nicaragua (Foidl *et al.*, 1996), a Chapman–Richards model was parameterized for seed yield over time ($b = 0.852$; $c = 3.466$ and a is iteratively modified to match seed yields at maturity and then assesses seed yield before maturity) (Trabucco *et al.*, 2010).

The annual average official interest rate from the Tanzanian National Bank, 16%, was used (www.bot-tz.org) as discount rate. Finally, to account for market effects, an 80% correlation between seed price and oil price was assumed (Goodwin, 2009; Dillen *et al.*, 2010).

As the marginal land-use types currently know no intensive human use, it was assumed that the land opportunity costs are negligible (Wahl *et al.*, 2009). The opportunity costs of land and labor were assumed to be zero as well.

Greenhouse gas reduction potential. The GHG reduction potential (in comparison with fossil diesel reference system) of the two pathways producing biodiesel (i.e., PW1 where seeds are sold, and PW2 where oil is sold) are calculated using

Table 1 Input data resulting from the yield potential modeling and the GHG reduction calculation. The Köppen climate zones encountered in each region are the following: Aw (Tropical Savanna climate), BSh (Arid Steppe climate), BWh (Arid Desert climate), Cwa (Temperate climate with dry winters and hot summers) and Cwb (Temperate climate with dry winters and warm summers)

Region	Köppen Climate Zone	Area Marginal land	Potential *Jatropha* yield				Pathway 1: Selling seeds			Pathway 2: Selling oil		
			Min	Max	Mean	Std	CO_2 reduction		Repayment time	CO_2 reduction		Repayment time
		[million ha]	[kg seed ha^{-1} yr^{-1}]				[t CO_2 ha^{-1} yr^{-1}]	[IPCC value US$ ha^{-1}]	[yr]	[t CO_2 ha^{-1} yr^{-1}]	[IPCC value US$ ha^{-1}]	[yr]
Arusha	Cwb	2.25	50	3250	945	690	0.179	2.5	61	−0.004	−0.1	–
Dodoma	BWh	2.19	150	3050	718	562	−0.012	−0.2	–	−0.240	−3.3	–
Iringa	BSh	1.58	150	3450	1053	924	0.299	4.1	36	0.129	1.8	85
Kagera	Aw	0.49	350	2850	1787	537	0.843	11.6	13	0.852	11.7	13
Kigoma	Aw	0.24	1350	3250	2490	476	1.488	20.4	7	1.631	22.4	7
Kilimanjaro	BWh	0.35	50	3350	767	592	0.025	0.3	441	−0.194	−2.7	–
Lindi	Aw	0.24	1950	3150	2701	173	2.175	29.8	5	2.201	30.2	5
Manyara	BSh	1.16	150	3050	979	528	0.225	3.1	48	0.043	0.6	255
Mara	BSh	0.51	450	2650	815	368	−0.032	−0.4	–	−0.216	−3.0	–
Mbeya	Aw	2.24	550	3750	1958	984	1.174	16.1	9	1.158	15.9	9
Morogoro	Aw	0.28	450	3450	2480	732	1.928	26.5	6	1.924	26.4	6
Mtwara	Aw	0.24	2450	3350	2909	94	2.266	31.1	5	2.356	32.4	5
Mwanza	Aw	0.48	750	2750	1523	353	0.666	9.1	16	0.604	8.3	18
Pwani	Aw	0.04	850	3350	2230	459	1.781	24.4	6	1.705	23.4	6
Rukwa	Aw	1.86	1050	3350	1832	494	0.969	13.3	11	0.957	13.2	11
Ruvuma	Cwa	0.87	750	3450	2711	166	1.926	26.4	6	2.037	28.0	5
Shinyanga	Aw	2.49	450	3050	1614	453	0.788	10.8	14	0.730	10.0	15
Singida	BWh	2.33	250	1850	567	304	−0.200	−2.7	–	−0.444	−6.1	–
Tabora	Aw	3.76	450	3250	1789	564	1.008	13.8	11	0.967	13.3	11
Tanga	BSh	0.17	50	3450	729	442	0.023	0.3	464	−0.207	−2.8	–

Table 2 Economic data used in analyses

Input	Cost (Tsh)	Output	Price (Tsh)	Source	Remark
Preparation of 1600 seedlings in nursery					
Seeds	800	1600 seedlings	–		
Polyethylene tube	33 600				
Polyethylene sheet	7200				
Labor	60 800				
Preparation of 1-ha land and establish 1-ha plantation					
1600 Seedlings					
Land preparation	9265	1-ha plantation	–		
Planting	184 952				
Cultivation of 1-ha *Jatropha* plantation during 5 years					
Irrigation	59 317	Seeds (per kg)	100	Messemaker (2008)	Average seed price in 2005
Weeding	123 527		300	Messemaker (2008)	Average seed price in 2008
Pruning	5932		180–500	Messemaker (2008)	Price range observed in 2008
Harvesting	207 per kg seed		150	Henning (2005)	Observed in 2005
			80	Van Eijck & Romijn (2008)	Observed in 2004–2005
			120–210	GEXSI (2008)	Observed in 2007
			210–471	Mulugetta (2009)	Observed in 2005
			100	Wiskerke *et al.* (2010)	
			200	Personal communication S. G. (2010)	
			120–150	Personal communication P. K. (2010)	
			500	Personal communication A. V. (2010)	
			100–500	Personal communication J. v. E. (2010)	
			Distribution seed price: Triangular PDF (80;300;500)		
Manual oil extraction of 1 L oil					
5 kg seeds		1 L oil	2000	Messemaker (2008)	
Labor	250		2000	Henning (2005)	
Depreciation of equipment	15.3		2000	Van Eijck & Romijn (2008)	
				Distribution oil price: PERT (1500; 2000; 2500)	
Making 10 pieces of soap (90 g)					
1 L oil		10 pieces soap	6000	Messemaker (2008)	
Ingredients	540		5000	Wiskerke *et al.* (2010)	
Packaging material	1355		5000	Henning (2005)	
Storage rent	700				
Depreciation of equipment	45				
Labor	1000				
			Distribution soap: Uniform (5000;6000)		

life-cycle assessment, as by Esthon *et al.* (2013) for Tanzania and by Ndong *et al.*, 2009 for West Africa. Because we need the GHG reduction potential in kg CO_2 ha^{-1} yr^{-1}, the generic *Jatropha* biodiesel life-cycle model developed by Almeida *et al.* (2011) was specifically adjusted for each Tanzanian region using region-specific parameters (e.g., yield, transport). This model accounts for all GHG emissions (CO_2, CH_4, N_2O, CFCs, etc.) created along the life cycle of the biodiesel [from field establishment, over the complete cultivation practices, oil extraction, and chemical conversion of oil into biodiesel, till the combustion in an engine, as described in section Production system under research – for a detailed description of the system boundaries of the generic model we refer to Almeida *et al.* (2011)], except for the emissions caused by land-use and ecosystem carbon stocks change. Timing of emissions is not considered in this life-cycle model. The time dimension is incorporated by using the carbon debt and repayment time concept brought up by Fargione *et al.* (2008).

Carbon debt and repayment time. Even though we selected only marginal land-use types, this land-use change can cause a carbon debt (*sensu* Fargione *et al.*, 2008; carbon debt is direct carbon stock loss triggered by land-use changes, minus the carbon stored in the stand of the new crop). Based on reported carbon stock fluxes (from soil and biomass) to the atmosphere after land-use changes in different land-use types in different geographical regions (Houghton & Hackler, 2001), we estimated the carbon debt caused by converting the marginal land into *Jatropha* plantations. The direct carbon stock loss triggered by these land-use changes throughout the different Tanzanian regions averaged around 55 t CO_2 ha^{-1} (average weighted according to area per region). As the marginal land-use types are currently not used intensively, it was assumed that the indirect land-use change effects on the GHG balance is negligible. Achten *et al.* (2013) estimated, based on literature, the carbon stored in a *Jatropha* plantation (above and belowground biomass) over different rotations to average around 44.1 t CO_2 ha^{-1} [i.e., 12 t C ha^{-1}, which is in line with the 8–10 t C ha^{-1} used by Bailis & McCarthy (2011) for C stored in aboveground Jatropha biomass in both India and Brazil]. This leaves a remaining carbon debt of 10.9 t CO_2 ha^{-1} which has to be repaid. This carbon debt value was used for all regions. Repayment time [yr] is the time necessary to neutralize this initial debt by Jatropha biofuel use reducing GHG emissions and is calculated by dividing the carbon debt [t CO_2 ha^{-1}] by the absolute GHG reduction rate [kg CO_2-eq ha^{-1} yr^{-1}] resulting from the life-cycle assessments (Fargione *et al.*, 2008; Achten & Verchot, 2011).

The data resulting from the yield potential modeling and the GHG emission reduction calculation are shown in Table 1.

Simulation model

Net present value. The cultivation of *Jatropha* will generate a value to farmers through the sale of seeds, oil, or soap. However, as the value of future returns is not perceived the same today, a time series of payouts from the investment in *Jatropha* production has to be discounted in order to allow for the objective comparison between production systems. The method of net present value (NPV) does so by calculating the present value of future cash flows. More formally, the NPV of an investment project is given by

$$\mathrm{NPV} = \sum_{t-1}^{T} \frac{C_t}{(1+r)^t} - C_0 \qquad (2)$$

where C_t is the net cash flow in year t and r the discount rate. The initial investment C_0 is not to be discounted as it is an expense in the reference period (Olson, 2004).

Model. In each iteration of the Monte Carlo simulation, the model draws a value from the different specified distributions (see section Economic data) and calculates the NPV for each of the potential pathways. This outcome can be treated as a potential outcome of *Jatropha* cultivation in the respective region. Running several iterations (5000 was enough to reach a stable mean) posterior PDFs are generated, representing the NPV of the different end products and production systems for the population of *Jatropha* farmers in a certain region. The nature of the model allows for scenario and sensitivity analysis. This allows to better understand the underlying mechanics of the model and the value creation. Moreover, to deepen the understanding of the results, break-even points can be calculated. Through an optimization, we can calculate prices and yields that would result in an expected NPV of zero. The break-even yields are calculated keeping the prices fixed at the average, and the break-even prices are calculated the other way around. Hence, investors and farmers can use this information to justify their expectations about *Jatropha* cultivation in Tanzania.

Results

Land area, yield, and greenhouse gas reduction

The area of marginal land, the climate classification, the potential yield, and the potential GHG reduction rates are shown in Table 1. Based on these figures, Tanzania has a large *Jatropha* potential. There is a total area of 23 763 600 ha of marginal land on which a potential 33 870 000 t *Jatropha* seeds could be produced annually. This production would lead to an annual GHG reduction of 15 282 700 t CO_2-eq by selling seeds and 12 889 400 t CO_2-eq by selling oil compared with a reference system using fossil diesel. The conversion of all this marginal land to *Jatropha* would, however, also lead to a total carbon debt of 1 307 000 000 t CO_2. Based on the average GHG reduction rates, this debt would only be repaid after 61 years. This average payback time is long because (i) some regions show a negative GHG reduction rate (see Dodoma, Mara, Singida in table 1) and (ii) some regions have a low GHG reduction rate resulting in long payback times (e.g., 441 years in Kilimanjaro, 464 years in Tanga). The GHG reduction in these regions is negative or very low mainly due to low yields. As GHG reduction is one of the major reasons to promote biodiesel production, it is important to identify the regions with a potential low payback time (e.g., 10 years).

Net present value for farmers in Tanzania

The mean NPV (US$), the probability of loss (i.e., probability of negative NPV in %) and the coefficient of variation of the different seed-processing pathways and investment scenarios per region are shown in Table 3 (more results in the supporting information).

For farmers deciding to start *Jatropha* cultivation with a one-time investment, the highest NPVs and lowest probability of loss are achieved by choosing to extract the oil themselves and sell the oil to biodiesel producers. The top five regions, Mtwara, Ruvuma, Lindi, Morogoro, and Kigoma, achieve an NPV of US$620–745 ha^{-1} with near to 0% chance of loss under normal conditions. With a one-time investment, an NPV of US$ 430–520 ha^{-1} can be achieved in the same regions by selling seeds to processors. Farmers choosing this pathway have 19–20% chance of loss. In case, one-time investing farmers in these regions opt to make and sell soap the NPV will be US$ 470–560 ha^{-1}.

Table 3 Repayment time (RT), net present value (NPV), chance of loss (CoL) and coefficient of variation (CV) of one-time and continuous investment in *Jatropha* aiming to sell seeds, oil or soap for regions in Tanzania. Top five regions are underlined

			Pathway 1: Seed			Pathway 2: Oil			Pathway 3: Soap		
	RT Seed	RT Oil	NPV (US$)	CoL, %	CV	NPV (US$)	CoL, %	CV	NPV (US$)	CoL, %	CV
One-time investment											
Arusha	61	–	207.5	32	1.27	207.5	6	1.04	144.4	26	1.52
Dodoma	–	–	87.2	37	2.46	146.2	11	1.21	94.8	32	1.82
Iringa	36	85	144.4	36	2.16	227.2	13	1.18	159.4	30	1.64
Kagera	13	13	293.4	22	1.27	437.6	0	0.51	317.5	13	0.87
Kigoma	7	7	432.5	20	1.14	628.4	0	0.41	466.7	10	0.77
Kilimanjaro	441	–	92.4	37	2.36	156.6	12	1.13	103.0	32	1.69
Lindi	5	5	473.8	20	1.09	686.8	0	0.36	510.2	10	0.72
Manyara	48	255	137.0	28	1.74	216.7	2	0.81	150.0	22	1.26
Mara	–	–	104.0	29	1.83	169.8	1	0.75	113.8	23	1.25
Mbeya	9	9	330.8	22	1.42	487.2	0	0.7	355.6	14	1.02
Morogoro	6	6	432.0	20	1.2	630.8	0	0.49	465.9	11	0.83
Mtwara	5	5	520.3	19	1.08	751.3	0	0.35	559.4	9	0.71
Mwanza	16	18	241.4	23	1.29	362.4	0	0.47	262.1	14	0.87
Pwani	6	6	383.4	21	1.16	560.9	0	0.43	413.5	11	0.79
Rukwa	11	11	304.4	21	1.24	449.4	0	0.49	328.7	13	0.85
Ruvuma	6	5	480.5	20	1.09	695.5	0	0.35	516.1	10	0.72
Shinyanga	14	15	261.0	22	1.3	388.0	0	0.51	281.0	14	0.88
Singida	–	–	48.6	40	2.83	93.5	11	1.09	55.8	36	1.94
Tabora	11	11	292.9	22	1.29	432.3	0	0.54	313.2	13	0.9
Tanga	464	–	85.2	33	2.23	144.1	5	1.01	94.8	27	1.59
Continuous investment											
Arusha			−43.6	82	−1.58	−19.1	73	−3.14	−36.6	81	−1.7
Dodoma			−55.0	87	−1.02	−36.1	81	−1.36	−50.4	87	−1
Iringa			−40.1	80	−2.04	−13.6	70	−5.48	−32.4	79	−2.2
Kagera			−1.1	54	−89.69	44.9	26	1.37	11.5	49	6.7
Kigoma			35.3	41	3.67	98.0	7	0.73	53.0	35	1.9
Kilimanjaro			−53.6	88	−1.07	−33.2	84	−1.49	−48.1	88	−1
Lindi			46.1	37	2.94	114.2	4	0.59	65.1	32	1.6
Manyara			−42.0	81	−1.49	−16.5	72	−2.97	−35.1	80	−1.5
Mara			−50.6	88	−0.98	−29.6	85	−1.2	−45.1	89	−0.9
Mbeya			8.7	56	14.09	58.7	34	1.61	22.1	52	4.6
Morogoro			35.2	43	3.84	98.6	13	0.86	52.8	38	2
Mtwara			58.2	35	2.52	132.1	3	0.55	78.8	29	1.4
Mwanza			−14.7	59	−5.54	24.0	34	1.99	−3.9	55	−16.2
Pwani			22.5	44	5.18	79.2	13	0.84	38.2	40	2.4
Rukwa			1.8	52	55	48.2	22	1.27	14.6	47	5.3
Ruvuma			47.8	37	2.87	116.6	4	0.59	66.8	31	1.5
Shinyanga			−9.6	58	−9.28	31.1	32	1.78	1.4	53	49.6
Singida			−65.1	94	−0.55	−50.8	94	−0.56	−61.2	95	−0.5
Tabora			−1.2	54	−80.31	43.4	28	1.48	10.3	51	7.6
Tanga			−55.5	92	−0.9	−36.7	91	−1.11	−50.4	93	−0.8

The NPVs of these one-time investment pathways are generally higher than the continuous investments for all sales pathways. In case of continuous investment, extracting and selling oil is still the best option in the same top five regions (NPV: US$ 100–130) per ha with 3–13% chance of loss). Selling seeds would result in an NPV of US$ 35–60 ha^{-1} (35–43% change of loss), whereas farmers selling soap would achieve an NPV of US$ 50–80 ha^{-1}.

Sustainability evaluation for Tanzanian civil society

Table 2 also shows the time needed to pay back the carbon debt (Table 1). The five regions with the highest NPV also show the lowest payback time (5–6 year), except for Kigoma (7 year). The region with the sixth highest NPV (Pwani) shows a payback time of 6 years.

The *Jatropha* biodiesel system achieves both a positive socio-economic balance (positive NPV) and a positive environmental balance (net GHG reduction) within 10 years in Mtwara, Ruvuma, Lindi, Morogoro, Kigoma, Pwani, and Mbeya. Considering these seven regions, there is a total area of 4 157 700 ha marginal land (17.5% of national total marginal land). This area has a potential production capacity of 9 491 800 t seeds yr^{-1} which would trigger a GHG reduction of 6 351 800 t CO_2-eq yr^{-1} by selling seeds and 6 470 800 t CO_2-eq yr^{-1} by selling oil, good for US$ 87 000 000–89 000 000 (Table 1) per year (US$ 21 ha^{-1} yr^{-1}). Note that, because of the carbon debt, these reductions become net reduction after 5–9 years of debt repayment. This means, e.g., for Mtwara region, that over a whole 20 year rotation period, one hectare could yield US$ 465 [= US$ 31× (20-year rotation – 5-year repayment time)] (Table 1).

As can be expected, the market price for the final product determines the profitability of *Jatropha* production to a great extent. Figure 2 shows the relationship between the assumed market price for *Jatropha* oil and the NPV in the Lindi region. The regression coefficient of 0.4 allows the reader to update the NPV calculations based on his or her guestimations both the Jatropha seed about future *Jatropha* oil prices under future market conditions or changes in natural oil prices.

Break-even thresholds

The break-even prices of seeds, oil, and soap are given in Table 4 for the five top regions. These prices are consequently higher for the continuous investing farmer than for the farmer choosing for a one-time investment. Generally, the break-even prices are similar to the current market prices (Table 2). Only the break-even oil price is considerably lower (one-time investment: US$ 0.90; continuous investment US$ 1.00, Table 4) than the market price (US$ 1.25, Table 2). The difference between one-time and continuous investment is even bigger for the break-even yield (Table 4). A farmer choosing for one-time investment needs to produce 232–324 kg seed ha^{-1} yr^{-1}. If he chooses to invest continuously his productivity should be 1216–1802 kg seed ha^{-1} yr^{-1} depending on the type of product he wants to sell. These break-even yields apply to the whole of Tanzania as costs and prices were assumed to be identical in all regions. Based on the yield estimations (Table 1), the yield thresholds indicate that all farmers across Tanzania have a chance to attain the break-even point after a one-time investment. This probability is not equally distributed throughout Tanzania. For farmers in Singida, the region with the lowest NPVs (Table 3), the probability to achieve break-even is 82–95%, whereas farmers in Lindi, the region with the highest NPVs (Table 3) have near 100% probability. However, such low yields will result in a low GHG reduction rate and consequently in long payback times (Table 1), which will result in a social cost instead of a social benefit.

Discussion and policy recommendations

The above shown results are based on combining three modeling steps. Each model has its own set of simplifications and uncertainties. However, the authors believe some interesting insight be gained from this exercise.

The financial analysis demonstrates the dominance of the one-time investment in *Jatropha* over continuous investment. This observation is mainly driven by the time value of money, represented by the discount rate.

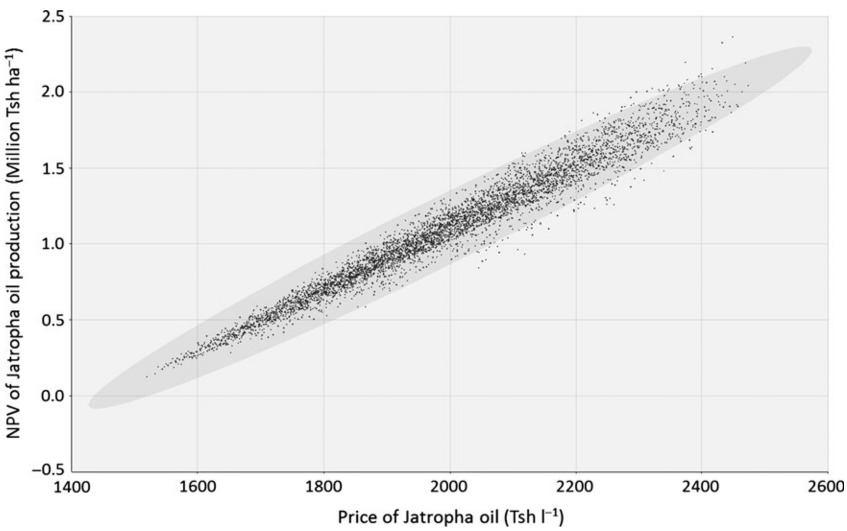

Fig. 2 Correlation between the assumed market price for Jatropha oil and the net present value of Jatropha oil production in the Lindi region.

Table 4 Break-even prices of seeds, oil, and soap for the top five regions in Tanzania and the break-even yield in Tanzania

	Break-even price (US$)	Break-even yield (kg seed ha^{-1})	Distribution of outcomes (%)	Difference seed-oil (Mean ± SD)*
Lindi				
One-time				
Seed (kg)	0.1	324	25	−210 ± 360
Oil (L)	0.9	232	43	
Soap (10 pcs)	3.2	303	32	
Continuous				
Seed (kg)	0.2	1802	21	−70 ± 90
Oil (L)	1.0	1216	46	
Soap (10 pcs)	3.3	1590	33	
Kigoma				
One-time				
Seed (kg)	0.1		18	390 ± 460
Oil (L)	0.9		48	
Soap (10 pcs)	3.2		34	
Continuous				
Seed (kg)	0.2		15	−110 ± 120
Oil (L)	1.1		50	
Soap (10 pcs)	3.3		35	
Morogoro				
One-time				
Seed (kg)	0.1		24	−200 ± 350
Oil (L)	0.9		42	
Soap (10 pcs)	3.2		34	
Continuous				
Seed (kg)	0.2		20	−60 ± 90
Oil (L)	1.1		46	
Soap (10 pcs)	3.3		34	
Mtwara				
One-time				
Seed (kg)	0.1		24	−230 ± 390
Oil (L)	0.9		43	
Soap (10 pcs)	3.2		33	
Continuous				
Seed (kg)	0.2		20	70 ± 100
Oil (L)	1.0		46	
Soap (10 pcs)	3.3		34	
Ruvuma				
One-time				
Seed (kg)	0.1		25	−215 ± 360
Oil (L)	0.9		42	
Soap (10 pcs)	3.2		33	
Continuous				
Seed (kg)	0.2		20	−70 ± 90
Oil (L)	1.0		46	
Soap (10 pcs)	3.3		34	

*Difference between NPV of pathway 1 (selling seeds) and NPV of pathway 2 (selling oil).

Typically, the discount rate in low-income countries is rather high, decreasing the discounted value of future returns on investment, and increasing the importance of immediate returns. Under continuous investment, the period of low yield is prolonged in comparison with one-time investment due to *Jatropha*'s maturation period and because part of the land stays unused for a prolonged period (e.g., for 1 ha available land, 0.5 ha stays unused for 10 year). Hence, the smaller annual financial flows at the start of cultivation under continuous investment decrease the NPV. Although continuous investment has several advantages in comparison with the one-time investment (e.g., continuous production over different rotations), they do not outweigh the benefits of immediate returns.

However, some Tanzanian farmers might not have the equity to make the required investment for the one-time investment pathway and the access to lending might be an obstacle as well. Possible support might be offered by the Tanzanian government or by private companies. As both farmers and the private actors have incentives to push one-time investment, coordination between both is realistic. This is confirmed by the fact that the majority of actual *Jatropha* cultivation occurs in outgrower schemes, where contracts could include that the company provides start-up inputs and that the farmer guarantees to sell the seeds or oil to the company (Martin *et al*., 2009). Hultman *et al*., 2012; however, consider that contract farming might not be the most interesting model for biofuel in Tanzania because of some potential deficits of the system (e.g., no further farmers' participation in other stages of the value chain; contracts often impose monoculture reducing individual flexibility; farmers often end up in unequal bargaining position; and, companies have become averse to contract farming due to a lack of a proper legal framework (Hultman *et al*., 2012).

Although selling oil requires an extra investment compared with selling seeds, the results show higher NPVs for selling oil than for selling seeds in all regions, which means that local oil extraction creates a net added value. Again, farmers have to be able to make the investment first. However, in this case, the incentive pattern of private companies and farmers does not overlap, because (i) companies have more efficient oil expelling infrastructure and (ii) the higher relative cost of *Jatropha* oil compared with seeds. On this step, the government might play a role. However, this would be conditional on the political choice to engage in *Jatropha* (taking into account possible rebound effects). If the Tanzanian government is convinced to invest, it is recommended to invest in local expelling infrastructure to keep profits with the rural population. As such, current results show, they can optimize farmer income while at the same time promote *Jatropha* production in those regions that provide an environmental benefit. These investments might even be aided by foreign capital if companies engage through the UNFCCC Clean Development Mechanism.

However, we would recommend the Tanzanian government to pay attention to the spatial planning of possible *Jatropha* investments concerning GHG emissions. We believe investments should be limited to those regions in which a net GHG reduction will be achieved within the first half of the *Jatropha* rotation period. In the Kyoto protocol, non-Annex 1 countries, like Tanzania, do not have greenhouse gas emission targets or a national GHG accounting. If the current project-based GHG balances are not made carefully, energy crops could easily be grown on locations that would render a long-lasting negative GHG balance due to carbon debt and leakage effects (Searchinger *et al*., 2008). The number of countries submitting national GHG balances like Annex 1 countries is likely to increase, reducing that risk. First steps in that direction are pleaded for in the ongoing REDD negotiations (Van Noordwijk & Minang, 2009). The necessity to meet certain emission criteria in order to be able to export the biodiesel as well as the sustainability image companies can gain are further incentives to invest in the regions where a net GHG reduction can be achieved within the first 10 years.

The results show that the regions with the highest NPV and the lowest probabilities of losses for the private farmers also have the best GHG balance. These regions have the possibility to produce *Jatropha* biodiesel in both an environmentally and socio-economically sustainable way. Note that these findings indicate that although the GHG problem is not a spatial problem per se, spatial approaches and solutions will be needed (Angelsen, 2009; Rudel, 2009).

This study also shows that, as expected, both the *Jatropha* seed yield and the *Jatropha* oil market price are the main factors determining the NPV of investments in *Jatropha.* Based on this insight, break-even yields and prices are calculated in this study. These thresholds are not calculated as criterion to decide to start with *Jatropha* or not, as breaking even should not be the goal. The aim is to inform on the minimum price and yield below which there is little chance of economic benefit in certain regions. Furthermore, these insights could be used to guide future research.

In this study, we looked at a production system defined and characterized as low input, small scale. The information on this production system and input and output prices were gathered first hand on the field, and also, the Tanzanian high-input, large-scale *Jatropha* systems were analyzed. The high-input, large-scale system mainly differs from the low-input system regarding fertilizer use. Whereas the low-input system considers no fertilizer input after the field establishment, the high-input system considers complete replenishment of the nutrients extracted from the field through seed yield harvest, by artificial fertilizers. This fertilizer application resulted in higher yields. The results obtained by analyzing this system in the same way (data not shown) were very different from the results obtained for the low-input, small-scale Tanzanian *Jatropha* system. In the high-input system, the NPV was negative in all regions, which confirms the findings of Segerstedt & Bobert (2013) on high-input systems. Mtwara, Ruvuma, Lindi, Morogoro and Kigoma (top five in this study) were ranked as the regions with the lowest NPV. This means that the cost of the extra inputs is not compensated by the increased yield triggered by higher inputs. As *Jatropha*'s yield response to inputs (chemical, physical, or management) is not well understood (Achten *et al.*, 2008), the optimal input-yield balance (both economic and environmental) is not known. The outcome of the analysis on the high-input, large-scale *Jatropha* systems indicates that the utilized inputs are beyond this point. As it is impossible to estimate how far these inputs are beyond the optimal, we did not report the figures. However, this analysis and this discussion indicate that, based on the current lack of knowledge, high-input systems have more economic risks than low-input, small-scale systems confirming Achten *et al.* (2010). This also corresponds to the conclusions of Wahl *et al.* (2009), who worked with lower discount rates and seed prices and included opportunity costs of (not strictly marginal) land and labor.

The approach used in this research has limitations, as it included several simplifications, inherent to the multidisciplinary scope of this study. The choice of the boundary conditions of the analysis can be considered in general relatively arbitrary. However, the choices made generally aim to cope with limited data availability. Like for many hyped crops, data on *Jatropha* are scarce (Achten *et al.*, 2008). This also relates to the way the yield uncertainty that the individual farmers face is included in the model. Based on a broad lack of knowledge on *Jatropha* yield, on the yield effects of agronomic practices, yield effects of genetics, etc. the yield uncertainty of individual farmers cannot be assessed. The authors believe that using the whole-yield variability of a certain geographic region is a suitable proxy for the farmers' uncertainty, because the farmers cannot make *Jatropha* knowledge-based decisions in the field selection. Moreover, the used yield assessment (i.e., Trabucco *et al.*, 2010) holds errors inherent to data and modeling limitations. Jatropha yield global map was validated against a limited number (15, mostly located in India) of available measurements of yield over surface (per ha). However, this yield validation is climatically distributed over semiarid and subhumid areas (annual precipitation ranging from 400 to 1500 mm with seasonal droughts), which roughly reflect precipitation regimes in Tanzania. Few recent studies indicate lower Jatropha yields (<1000 kg ha^{-1} yr^{-1}) in Eastern Africa (Iiyama *et al.*, 2013; Van Eijck *et al.*, 2013), although reporting data mostly measured per tree (rather than per surface) which may have not reached yet full maturity. In addition, the used yield model indicates potential achievable yields under optimal-suboptimal genetic and agronomic conditions, while most crop productivity in Africa in reality undergoes large yield gaps (Tittonell & Giller, 2013). Uncertainty in the yield model was also assessed spatially by Trabucco *et al.* (2010), by applying a Monte Carlo analysis over yield model parameterization, which indicates for this specific study highest model uncertainties in the region of Mbeya, Tabora, and Rukwa.

The uncertainty on the yield and its effect on models or economic and environmental evaluations has been discussed by several authors (Almeida *et al.*, 2011; Mshandete, 2011; Van Eijck *et al.*, 2012; Segerstedt & Bobert, 2013) and may indeed not be underestimated. In our exercise, we used global modeled potential Jatropha yield. However, yields are not always as expected (see yield ranges). Therefore, the values shown in this study should be handled with care.

However, this study shows that an approach explicitly taking into account these uncertainties can yield interesting results and insights on an upcoming biodiesel crop like *Jatropha*. NPV is a simple and basic, but robust economic indicator. It is well known that the discount rate is an important factor in the NPV calculation. Therefore, the average official interest rate from the Tanzanian National Bank was used. Because we focused on *Jatropha* cultivation on marginal lands only (no cropland, but potentially public grazing land), we did not consider opportunity costs of labor and land and indirect land-use change. Also, we did not compare the NPV of investments in *Jatropha* with potential NPV of investments in main agricultural crops in Tanzania, e.g., maize, because the lands considered available for *Jatropha* are not suitable for agricultural production. This approach might have resulted in an overestimation of the economic potential of the different *Jatropha* options for the private farmers. Van Eijck *et al.* (2012) indeed conclude that Jatropha performs economically best with family labor and/or with low (or no) opportunity cost. Therefore, the NPVs given in Table 2 should be considered with care. Further, it has to be noted that the current status of the marginal lands (no commercial production) might be different from what it appears. Although not in commercial production, lands can perform other important functions for local communities (e.g., grazing or energy provisioning) (Achten *et al.*, 2013; Maes & Verbist, 2012). Also, the status might have been different in the past or might change in the future. These issues also play a role and might shed a different light on farmers' options. Although interesting questions can still be posed regarding these issues, the potential effects of this potential changes are beyond the scope of this paper. Further, no data are available, or reliable predictions can be made regarding such changes.

However, the difference between economic performance and environmental performance in this study is so large, which in terms of sustainability (environmental and socio-economic), and we can conclude that, even when the economic performance of the *Jatropha* system is overestimated, the environmental performance is the most restrictive.

This study estimates the economic potential of *Jatropha* biodiesel production from the viewpoint of both the private farmers and the civil society in Tanzania. Even with part of the data and calculations being a bit coarse, we believe the approach offers several robust and interesting findings, which can support policy making regarding this potential biodiesel crop.

Further, the authors believe this work shows strong and innovative interdisciplinary modeling work, which could be considered a scientific contribution as well.

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